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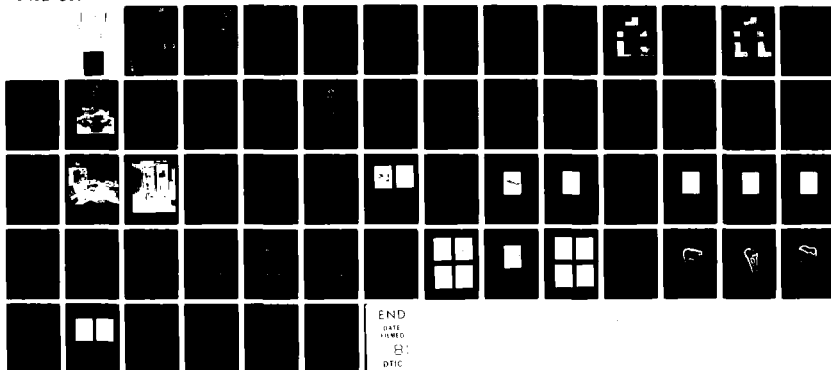
SCREENING PANORAPHIC MAXILLOFACIAL X-RAYS BY ELECTRONIC EQUIPM--ETC(U)

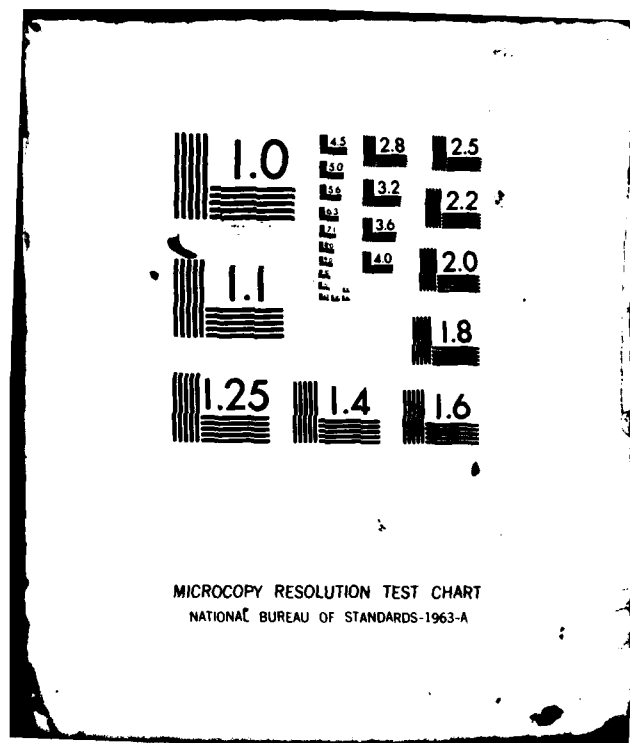
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SCREENING PANOGRAPHIC MAXILLOFACIAL X-RAYS

BY ELECTRONIC EQUIPMENT

Final Report

Mortimer L. Shakun

April 1980

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Under control of a heuristic program, a flying-spot scanner is used to digitize selected portions of a panoramic dental radiograph. These digitized signals are filtered mathematically and the resulting smoothed and enhanced signals are analyzed by feature recognition programs. The outlines of existing teeth are then recreated by the computer and displayed on a graphic display terminal.		

FORWARD

The purpose of this investigation was to develop a working model of a computerized picture-scanner/image-processing system to evaluate panoramic dental radiographs. A flying-spot scanner controlled by a heuristic computer program digitized select regions of the radiograph and the resulting signals were stored in an IBM 1130 computer. Appropriate mathematical filtering techniques were applied to these signals, and the resulting enhanced signals were then analyzed by feature recognition programs which then reconstructed the images of existing teeth and displayed them on a graphic display terminal.

Although the panoramic radiographs contain a considerable amount of noise generated by the blurring-out of structures not in the plane-of-focus of the x-ray imaging system, and non-linearities in the intensity of the modulated x-ray beam effecting the film, it was possible to separate the information content from the noise with a moderate degree of reliability.

Another interesting aspect of this project was the use of the radiograph itself as the storage medium for the image. Only small, pre-determined areas of the film were scanned and stored in the computer at any given time. This permitted the system to operate with a relatively small computer system (16 K memory) and one disc-pak.

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Dental X-Ray Computer Project

Final Report

I. Project Overview

Panoramic dental radiographs display the entire dental apparatus (the teeth and their supporting and surrounding structures) on one continuous 5" x 12" film.

The objective of this project was to develop a working model of a computerized picture-scanner/image-processing system for obtaining information relative to the dental status of a person using a panoramic dental radiograph as the source document.

The information, in machine readable form, could then be used to build a data-base of standardized "dental profiles" that could be used to:

- a) maintain a chronological dental history for a given patient;
- b) check for pre-existing conditions at a certain point in time for insurance purposes, eligibility for dental care by certain agencies such as the VA;
- c) provide a file for possible identification of disaster victims based on information of existing dental conditions (restorations, missing teeth, prosthesis, etc) of the victim(s);
- d) perform epidemiological dental health surveys for various sub-populations of the data-base over time; etc.

This system would include:

- a) a scanner for digitizing the image of a dental panoramic radiograph;
- b) a computer to control the scanner, process the digitized picture information, operate devices used to monitor operation of the scanner and display the results of the picture processing procedures;

- c) an interface between the scanner and computer for the transmission of digital information from the computer to the scanner (D/A conversion) and transmission of picture information from the scanner to the computer (A/D conversion);
- d) appropriate display devices to provide visual displays and hard copy of the image processing results; and
- e) the necessary computer programs to drive and control the scanner, process the picture information and control the various display devices.

There were three major developmental components in the project:

1. Hardware Development

- design and develop the optical scanning equipment;
- select a suitable computer system to drive the scanner and process the picture information; and
- design and construct the interface required to link the scanner to the computer, including the necessary A/D (analog-to-digital) and D/A (digital-to-analog) converters.

2. Software Development

- develop the computer programs to:
 - a) transmit information between the scanner and computer;
 - b) drive the scanner, including control of the scanning CRT and measurement of the density;
 - c) process the digitized picture information; and

d) control and operate the various display devices.

A description of each of these major project components is presented in following sections of this report.

3. Picture Processing Algorithms Development

- evaluate the information content of the panoramic dental radiographs produced by the Panorex Dental X-Ray machine, and design the image processing heuristics for collecting and evaluating picture information from the radiograph.

II. Mathematical Concepts of Picture Processing

The theoretical basis of picture, or image, processing is the ability to represent a picture (or radiograph) as a mathematical function, $f(x,y)$, of the optical density of the picture at coordinate point (x,y) in the spatial domain, or alternatively, as a function of frequencies and amplitudes, $F(u,v)$, in the frequency domain. The specific mathematical technique used to transform the picture function from one domain to the other is the Fourier transform (and its inverse).

In general, objects or areas are recognized in a radiograph by first detecting the boundary delineating the area, and then applying some type of classification process to the shape or general density level of the delineated area to identify the object.

There are two basic attributes that are used to describe the visual appearance of a "boundary" in a radiograph:

- a) contrast, and
- b) detail

Essentially, radiographic contrast is the amount of density difference between adjacent areas in a radiograph. Radiographic contrast is said to be "high" when there are only a few recognizable density levels between the black and clear areas in a radiograph; this is often referred to as "short-scale" contrast. When many different density levels can be recognized, the radiograph is said to have "low" radiographic, or "long-scale" contrast.

Figure 1a illustrates the density plot across a boundary on a radiograph with high radiographic contrast. Note the marked difference between regions A and B. The plot of the change in density across a boundary with low radiographic contrast is depicted in Figure 1b; note the relatively small

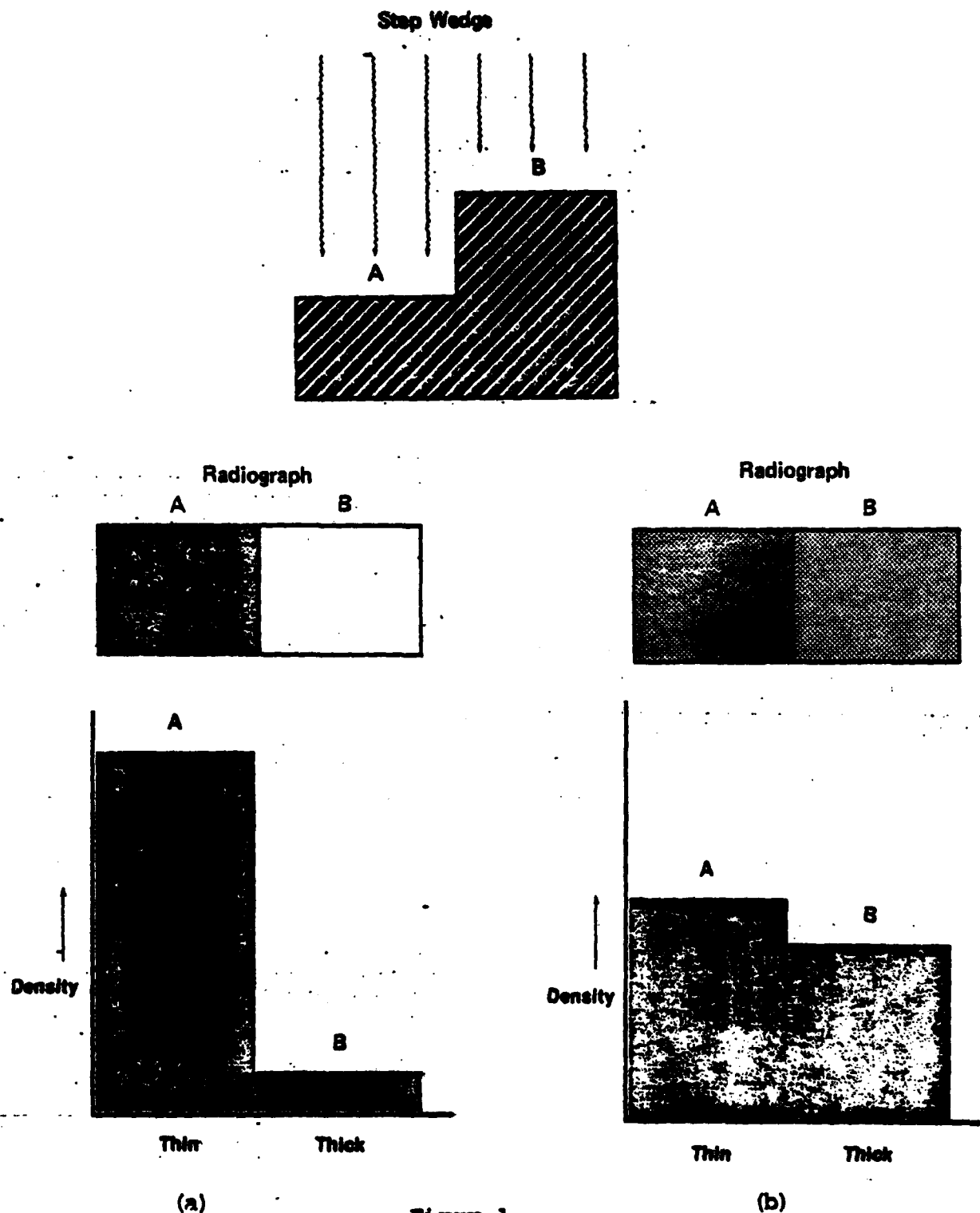


Figure 1

The illustration on the left depicts the "radiographic appearance" and density plot of a high-contrast radiograph of the step wedge shown above; the illustration on the right corresponds to a low-contrast situation.

difference in densities between regions A and B in the plot. It is important to note that in order for the human eye-brain system to recognize a boundary in a radiograph, the difference in densities between the regions on either side of the boundary must be greater than a certain critical value.

From an image-processing point-of-view, image contrast is a significant factor in the picture representation and interpretation in the spatial domain, and critical density differences must also be defined for the computer to "recognize" the existence of a boundary.

The abruptness of change in density between two discernable areas in a radiograph is referred to as radiographic detail.

Density plots across a radiograph boundary with good and poor detail are illustrated in Figures 2a and 2b, respectively.

In general, radiographic contrast and detail are subjective terms. The mathematical concept of a gradient combines these two concepts into a single quantitative measure by taking into consideration the rate-of-change of density in a given direction over a given distance in the picture or radiograph. In computerized picture processing, it is the magnitude of the gradient in a given area of the picture that is ultimately used to identify boundaries.

It is known that sharply defined boundaries in the spatial domain are associated with high-frequency components in the frequency domain; fuzzy or soft boundaries have a significant low frequency component. By removing the low frequency component(s) from the frequency domain representation of a picture by the use of a "high-pass filter", and using the inverse Fourier transform to return to the spatial domain, the resulting "picture" would appear

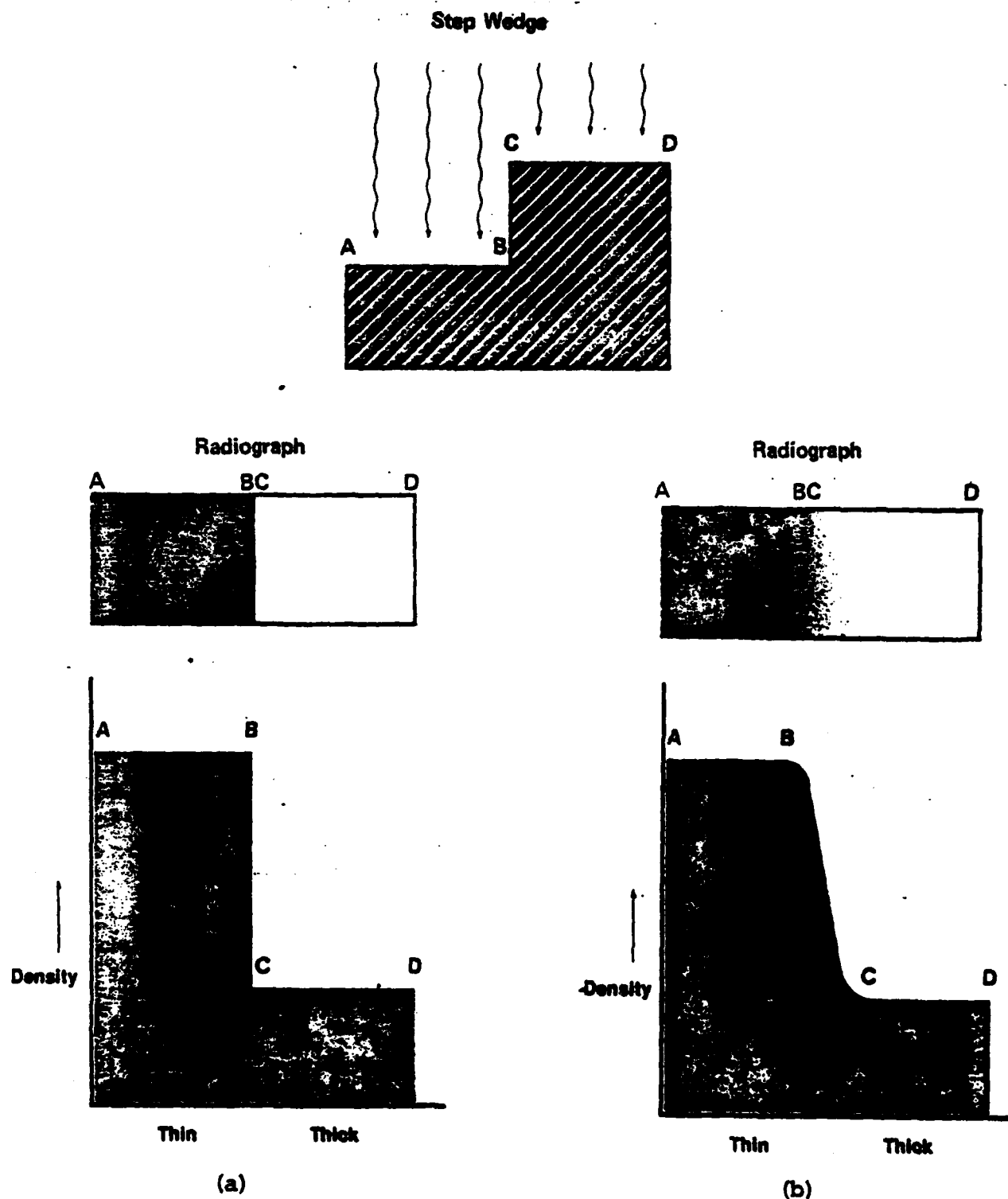


Figure 2

The illustration on the left corresponds to a radiograph of given contrast with good detail - note the abrupt change of density between the image of the thick and thin portions of the step wedge. The illustration on the right corresponds to a radiograph with the same contrast, but with poor detail - note the relatively wide transition zone between the areas representing the thick and thin parts of the step wedge.

to be sharper in the sense that density changes corresponding to boundaries would appear more abrupt over a given distance (i.e. for a given region of the picture, the density gradient would be greater after this filtering or enhancement operation was applied).

From this brief discussion, it is apparent that the visual detection and recognition of a boundary in a radiograph depends on two factors:

1. that there be a minimal absolute difference between the densities in the region on either side of the boundary - that is, there must be sufficient contrast between the regions; and
2. that this density change occur over a very small distance so that the boundary is sufficiently "sharp" - that is, the radiograph must possess sufficient detail.

The recognition of boundaries in an image processing system is also based on the detection of a gradient of suitable magnitude. The computerized system has the advantage, however, of being able to "mathematically enhance" the image by suitable filtering techniques before applying boundary recognition criteria.

III. The Panorex Dental X-Ray Imaging System

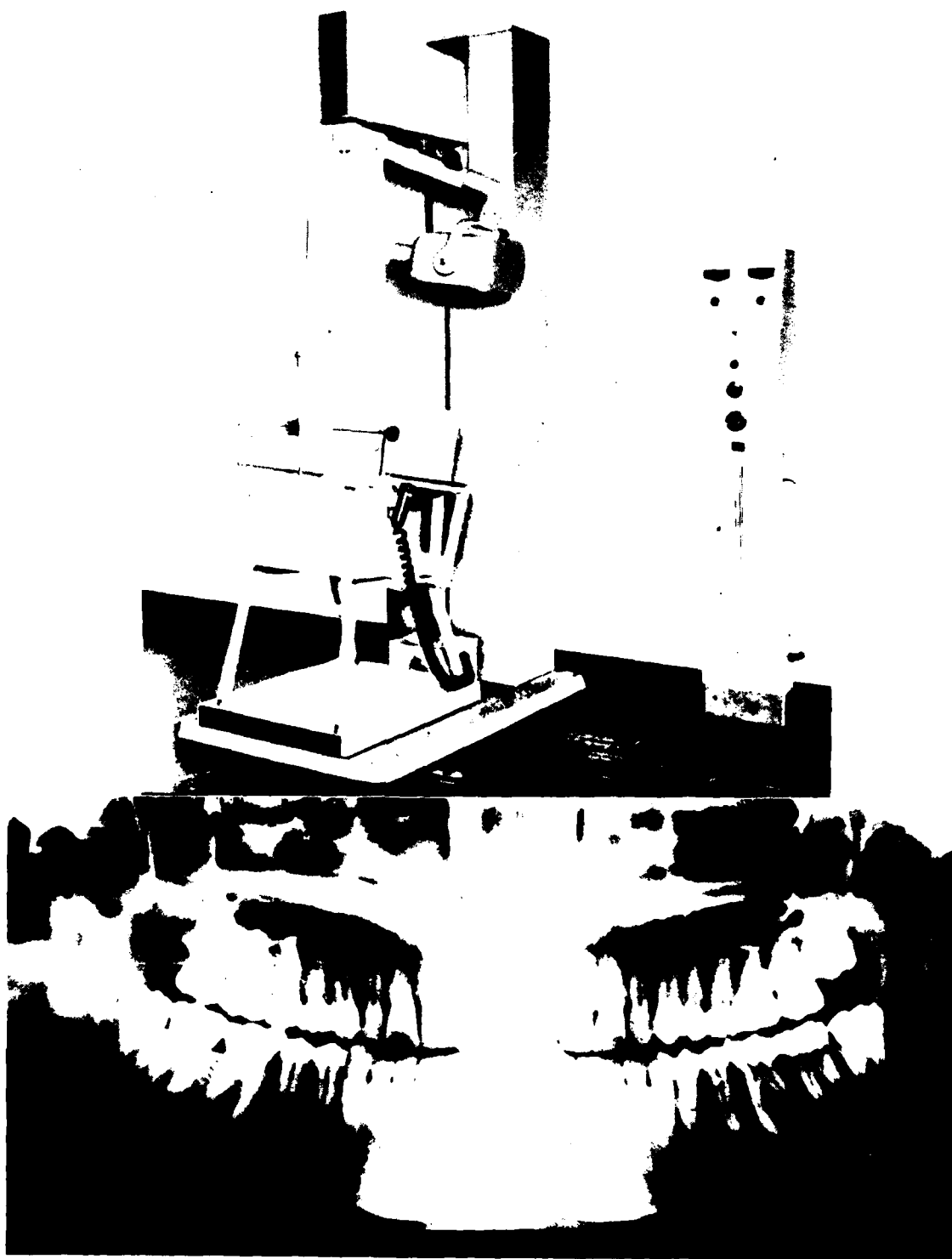
While objects themselves may have sharp, well-defined physical boundaries, the radiographic images of these boundaries never appear as sharp or as well-defined. This degradation of boundary detail is an inherent feature of all x-ray imaging system and is due to such factors as:

- finite focal spot size, rather than a pin-point source;
- scatter of the x-rays by the object itself;
- secondary radiation;
- quantum effect of intensifying screens;
- film grain size;
- movement of object and/or x-ray tube during the exposure.

The Panorex Dental X-ray machine was used for this project as it produces a display of each half of the head on a well defined 5" x 5" area of the 5" x 12" panoramic dental film. See Figure 3. The design of this machine is based on the principal of curved-surface tomography.

Conventional x-ray imaging techniques produce a radiograph of an object in which all the structures in the path of the x-ray beam are super-imposed upon one another in the resulting radiograph.

Tomography is an imaging technique that can produce a relatively sharp image of a layer within an object, with the images of the structures above and below the layer of interest blurred out. The degree of blurring of these structures outside the desired layer is dependent on the distance these other structures are above or below the layer of interest - the further they are removed, the greater the blurring effect. The tomographic technique virtually eliminates the effect of super-position of structures above and below the layer of interest.



Panorex unit and an example of the panoramic radiograph made with this unit. The x-ray tube and the cassette holder revolve around the patient's head. A thin beam of x-rays emerges from the tube head, passes through the patient, and then enters the slit opening shown in the cassette holder. The cassette in the cassette holder moves behind the slit at the same speed as the jaw is scanned by the x-ray beam. (Courtesy X-Ray Manufacturing Corporation of America, Great Neck, N. Y.)

Figure 3

The net effect is to produce an x-ray image of a desired layer in an object that portrays the structures in the layer of interest with greater clarity and visualbility than could be produced by a conventional stationary technique.

Mechanically, the x-ray tube and film carrier of the Panorex machine are connected to each other, and designed to rotate about a rotation-center in the object. The x-ray beam is collimated into a narrow beam, or sheet, with a rectangular cross-section. The film carrier has a slit that corresponds to the shape of the collimated x-ray beam, so that only a portion of the film the same size as the beam is exposed at any given time. As the tube and film carrier rotate about the rotation-center in the object, the film is transported across the slit in the film carrier at a rate such that the image of the teeth appears "sharp", while the structures on either side of the teeth are blurred out due to their apparent motion relative to the film.

For a fixed film speed, the thickness of the layer that appears sharp, (i.e the "focal trough") varies with the angle of movement of the x-ray beam relative to the object. If the x-ray beam moves through a large angle, the trough is narrow; if the angle is small, the band of acceptable focus is wide. For the Panorex machine, the focal trough is about 1/2" to 2/3" wide.

The rotation-center is just lingual to the third molars on the side of the head opposite to the side that is being imaged. Mid-way through the exposure, the center-of-rotation is physically relocated to the opposite side of the patient's head to permit imaging of the other side. This is accomplished by physically moving the patient the required distance relative to the x-ray

tube/film carrier component. During this shift of rotation-centers, the x-ray beam is cut-off, but the tube-head and film-carrier continue to rotate about the object. See Figure 4.

The x-ray beam is again turned on when the tube-head/film-carrier has been positioned over the new rotation-center. This shut-down of the beam results in a clear band being produced in the middle of the film and the images of the teeth immediately adjacent to the mid-line appear in both halves of the radiograph.

The radiographic detail of films produced by the Panorex system is somewhat less than that of conventional x-ray imaging systems. The two major factors responsible for this image degradation are:

1. movement of the x-ray source, film or object relative to one another: this results in a decrease in the sharpness of the resulting image; even though all of these components are suppose to be at relative rest to one another, there is still a very small, but limited amount of motion between the object and the film which results in a slight fuzziness in the radiograph; and
2. the use of a film cassette and intensifying screen to reduce the total amount of radiation required to produce the radiograph: the screens introduce some level of quantum-noise that also has a slight (but unavoidable) negative effect on image detail.

There are several other factors that also effect the density of the radiograph produced by the Panorex machine. Since the exposure time and target-film distance

are fixed in the Panorex system, their effect on the radiographic density of the resulting radiograph is a constant. Assuming proper film processing procedures, the variable factors which affect the image density are:

<u>Factor</u>	<u>Effect on Density</u>
kilovoltage	increases with Kvp
milliamperage	increases with ma.
film	increases with film speed
screen	increases with speed
object size	increases with thickness

It is important to note that while the film and screen may be standardized for all subjects, and the ma set at a fixed value for all exposures, the Kvp is a function of the physical size of the subject's head. Individual variation in bone structure, bone density, etc. are not quantitatively considered when setting the Kvp. This results in a considerable variation in the over-all density level between radiographs of different subjects.

While there is a specific manner in which the head is positioned relative to the rotation-centers of the machine, the upward/downward tilt of the head is only approximate (it is based on a 5-degree downward inclination of the ala-tragus line). This results in considerable variation in the shape of the dental arches in the resulting radiograph (specifically, the degree of convexity of the arches), and also in the position of the images of other structures of the skull bones relative to the images of the teeth.

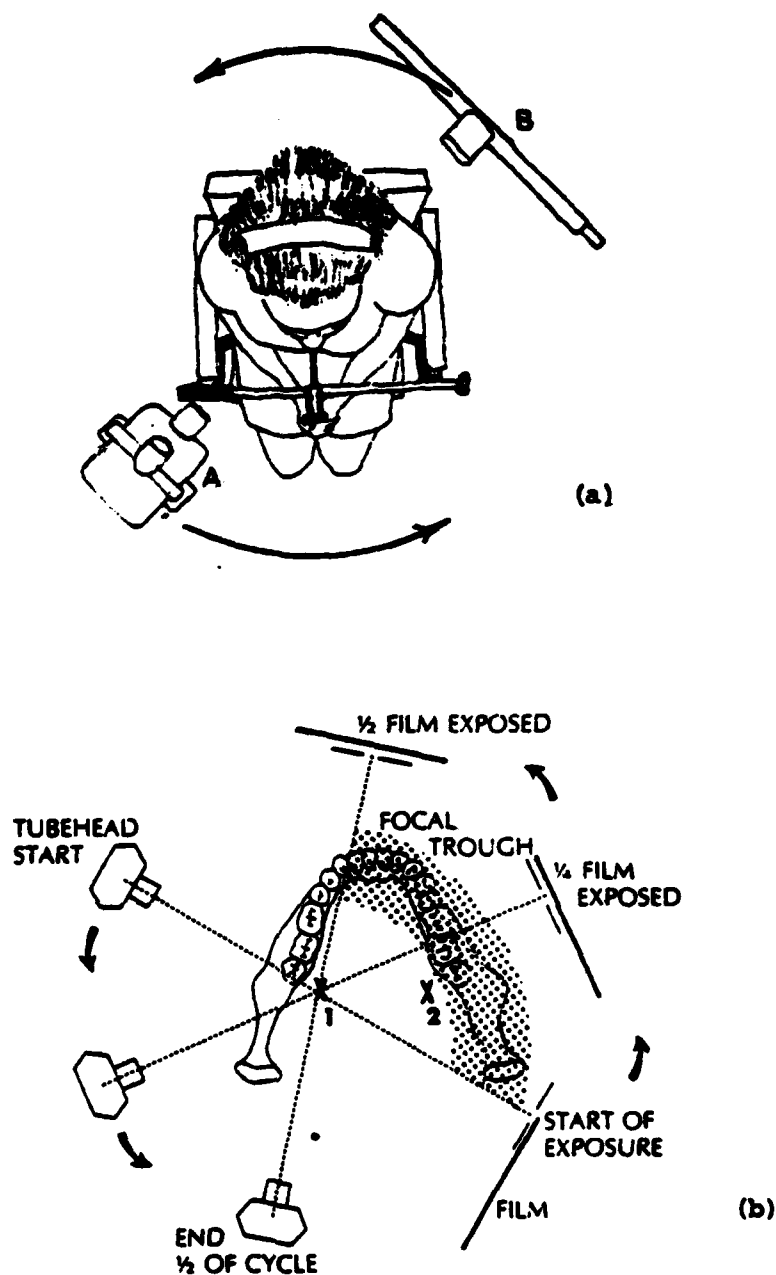


Figure 4

Principle of operation of the Panorex Dental X-ray machine. (a) Relationship of the tube head (A) and film transport mechanism (B) to the patient. (b) Relationship of centers of rotation and focal trough to patient's jaw, as seen from above.

Thus, while all panoramic radiographs contain the same basic information, they are subject to considerable variation with respect to over-all density, contrast and detail, shape of the dental arches, and "noise" due to the images of other structures of the skull interfering with the images of the teeth.

There is also a certain degree of magnification in the resulting radiographs that is not constant over all parts of the image. While this variability is no problem for the visual reading of these radiographs, it does present significant problems for a computer-based image processing system.

IV. The DRCP Picture Scanning & Processing System

A. System Hardware:

One approach to picture processing is to digitize the entire picture and have it core-resident in the computer during processing. Considering the nature of the information that is to be extracted from the radiograph, the sampling rate could not be less than 200/inch. Therefore, for a 5" x 5" radiograph, 1,000,000 data points would have to be stored; and if a higher sampling rate were required to detect significant density variations, this number would be even larger.

The approach adapted for this project was to use the panoramic radiograph itself as a "random access storage medium". This was accomplished by designing a flying-spot scanner with no inherent raster-generating capability, but rather with the ability to position the spot at an (x,y) coordinate supplied by a computer, and then return the density at that point back to the computer. Thus, picture-image information of a small section of interest of the total radiograph only need be in the computer memory at any given time. This concept greatly reduced the size of the computer memory required.

Based on this concept, the DRCP scanning system was designed and fabricated with the following components:

1. a flying-spot optical scanner;
2. an IBM 1130 computer;
3. display devices.

See Figure 5.

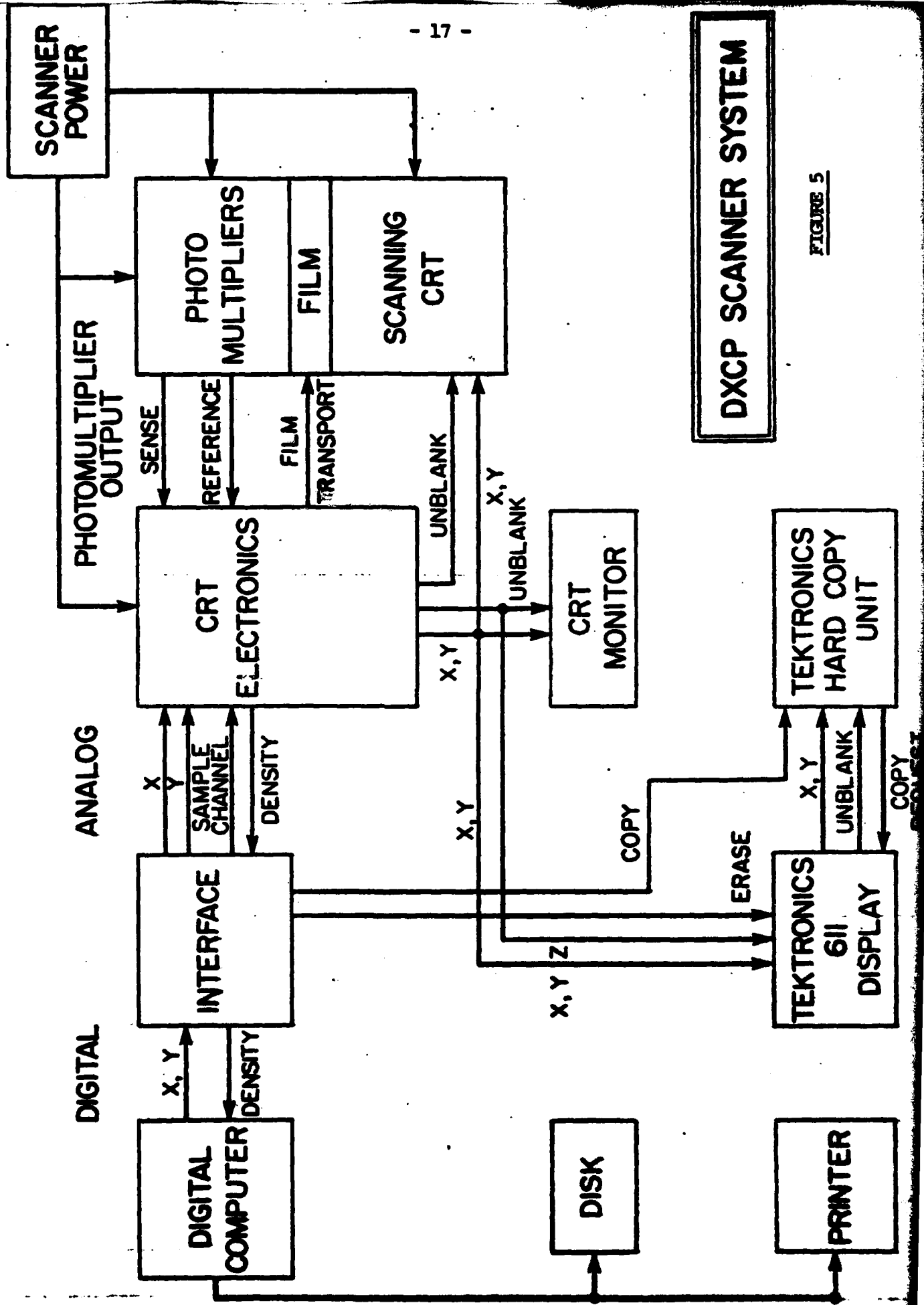


FIGURE 5

The scanner is a flying-spot design using a Litton Industries Micropix Ultra-High Definition CRT (Model No. L-4123) with a P-16 phosphor. Magnetic focusing and deflection is used, and the CRT is housed in a Litton Model 1031 Magnetic Shield to minimize the effect of stray magnetic fields from affecting the spot size and position.

The amount of deflection of the spot is dependant on the analog signal resulting from the D/A conversion of the x and y coordinates transmitted to the scanner from the computer. The scanning matrix is 2048 x 2048 points over a 5" x 5" area, and the spot size was less than 50m on the CRT face plate. The x and y scan axes were orthogonal to within ± 5 degrees; beam positioning time is less than 10 microseconds. See Figure 6.

The system uses two RCA-4517 10-stage photomultiplier tubes to convert the light beam from the scanning CRT to a signal proportional to the density of the radiograph at a given scan point. After passing through the film, the transmitted light beam is split by a half-silvered mirror so that 50% of the transmitted light goes to a reference photomultiplier, and 50% of the light goes to a measurement photomultiplier. See Figures 7 and 8.

The output signal is the ratio of the outputs of the two photomultipliers; this technique has the advantage of eliminating the effects of variation in CRT spot intensity due to fluctuations in line voltage, etc.

SUB SYSTEM ONE

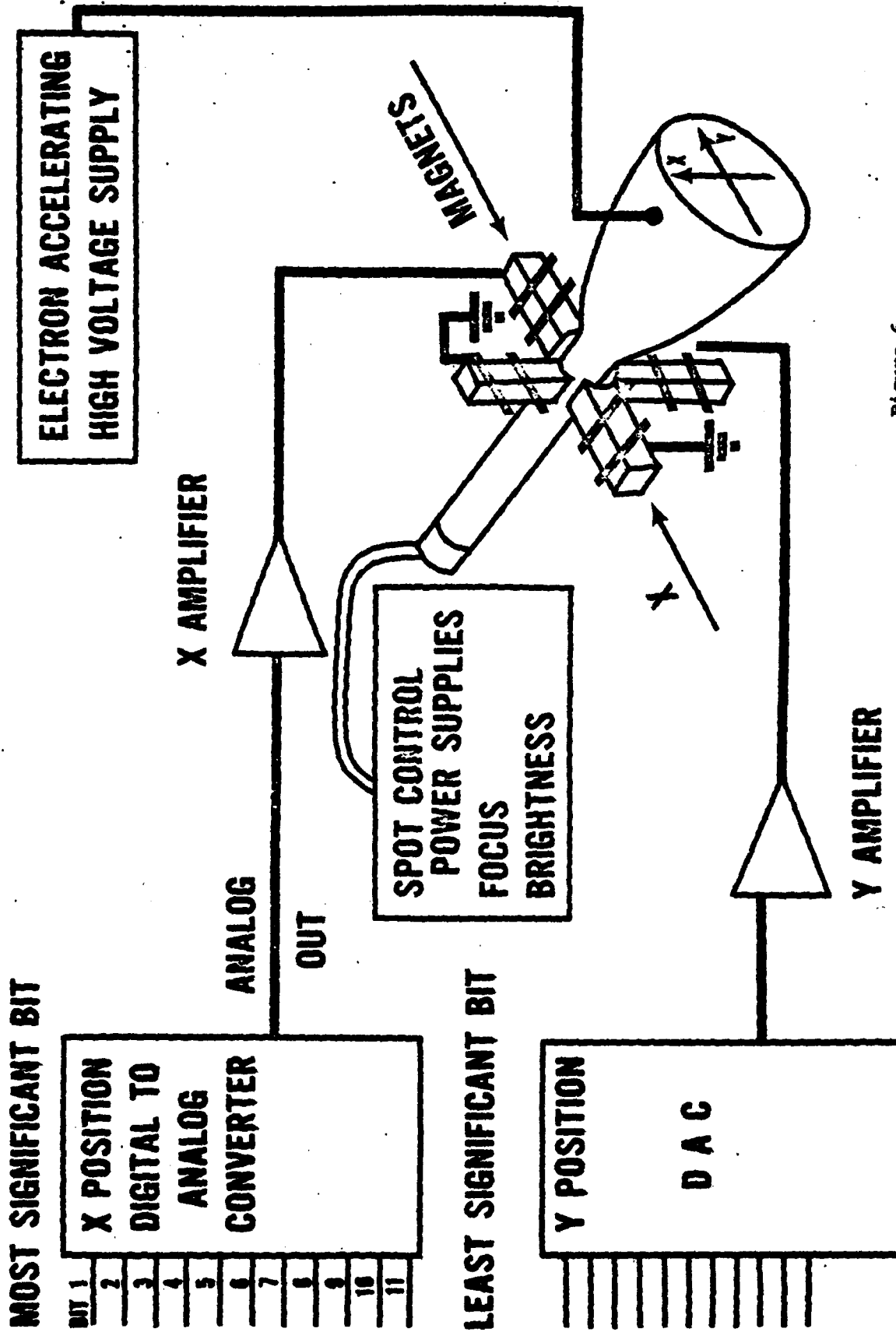


Figure 6

The scanning CRT subsystem.

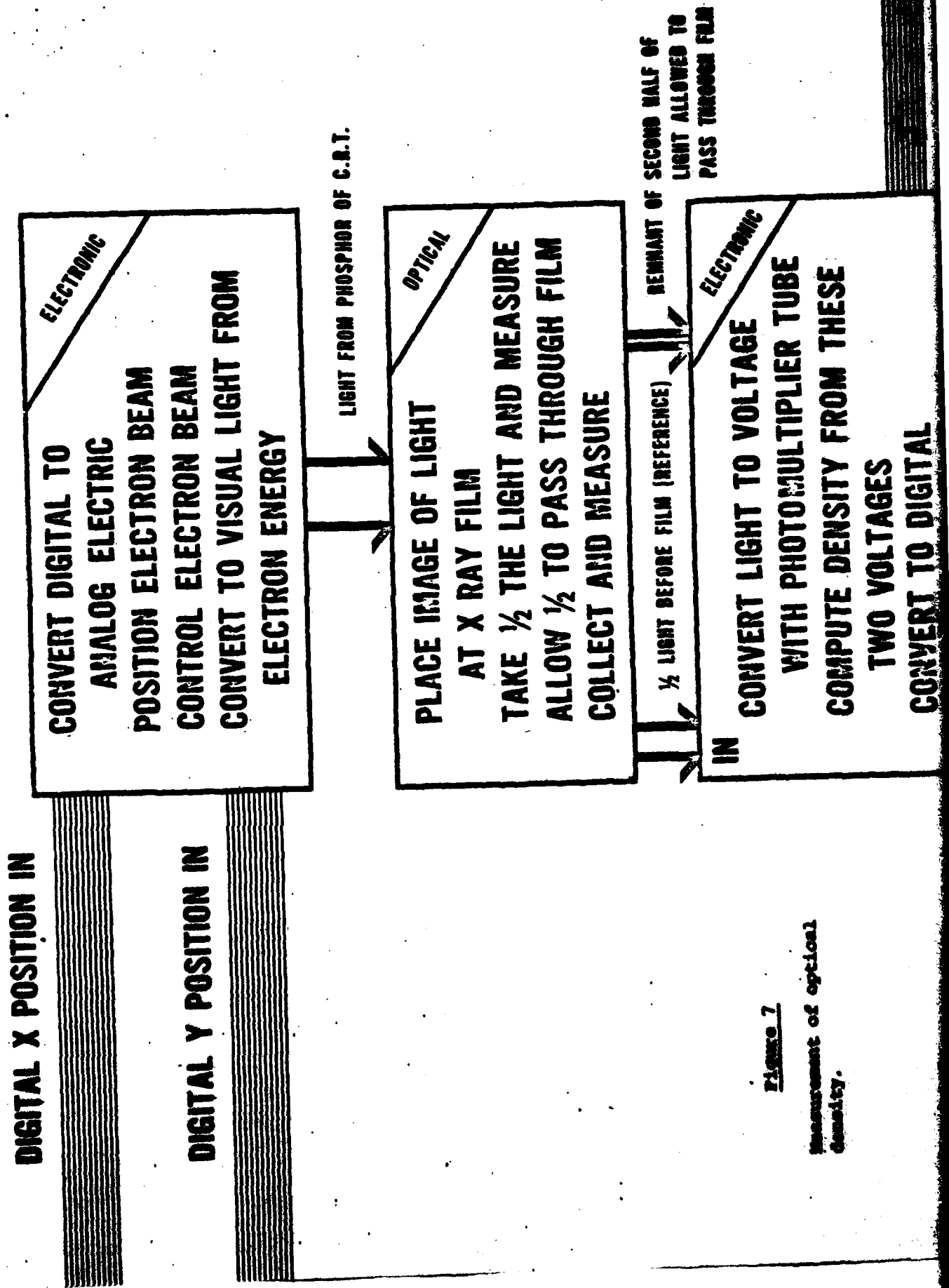


Figure 2
Measurement of optical
density.

SUB SYSTEM TWO AND CATHODE RAY TUBE

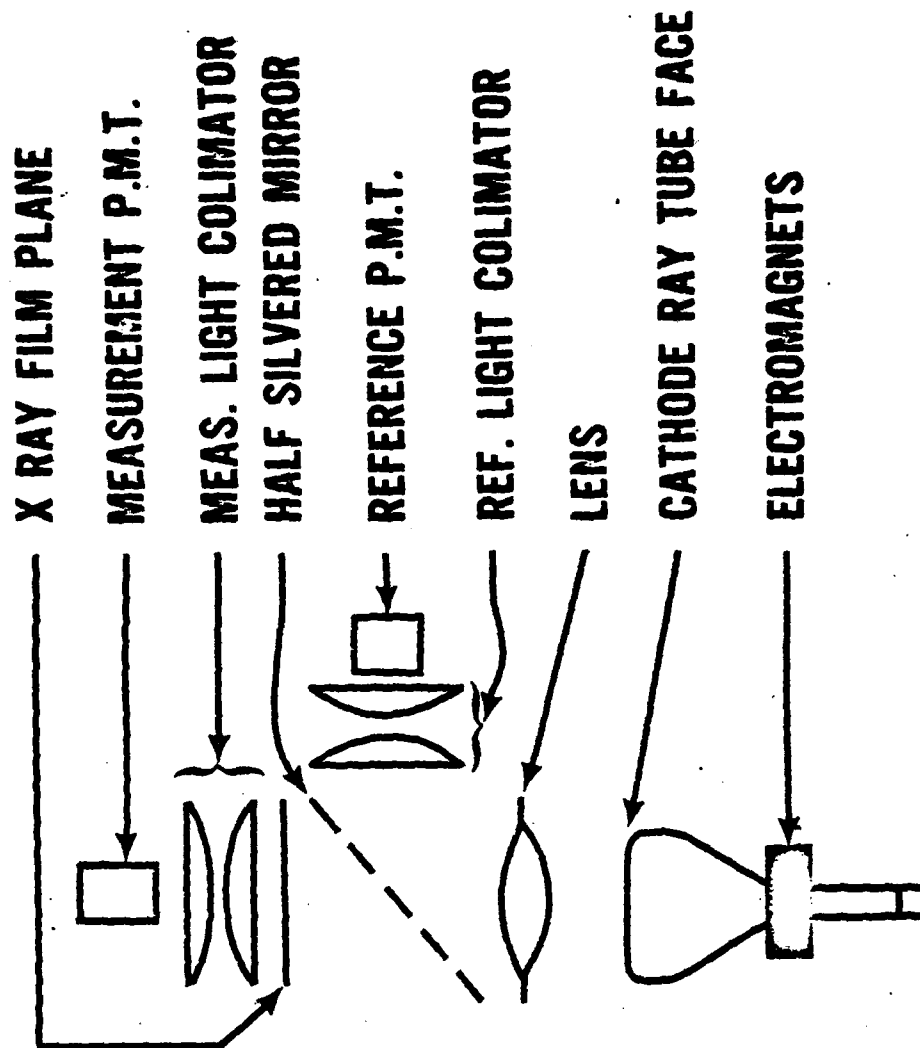


Figure 8 - Subsystem for optical density measurement.

Timing circuits control the integration time of the photomultipliers, and at the end of the integration period, the PMT output signal is fed to an A/D converter, here it is converted to a digital signal corresponding to the density. Density returns are digitized to 64 levels, corresponding to an absolute density of 0 to 2.05. See Figure 9.

All necessary power supplies, timing circuits and related electronics were housed in one cabinet, and the CRT and PMT's were built into a second cabinet.

The computer used was an IBM 1130 with 16K core memory, one disk, and a line printer.

There were several display devices incorporated into the system that permitted real-time visualization of the scanning process, and selective output of either the scanning process or the results of processed information.

For real-time monitoring of the scan process, a Tektronix Type 602 Display Unit with a 5" CRT with a moderately long-persistence phosphor was selected. This device was incorporated into the scanner hardware and provided a direct visualization of the movement of the spot of the scanning CRT. A Tektronix Type C-30A camera with Polaroid Land roll-film camera-back was provided to take pictures directly from the face of the 602 unit.

A Tektronix 611 Storage Scope with a 2311 hard copy unit was available to display (and hold) graphic output from the computer, and the 1130 line printer was available for text printing. See Figures 10 and 11.

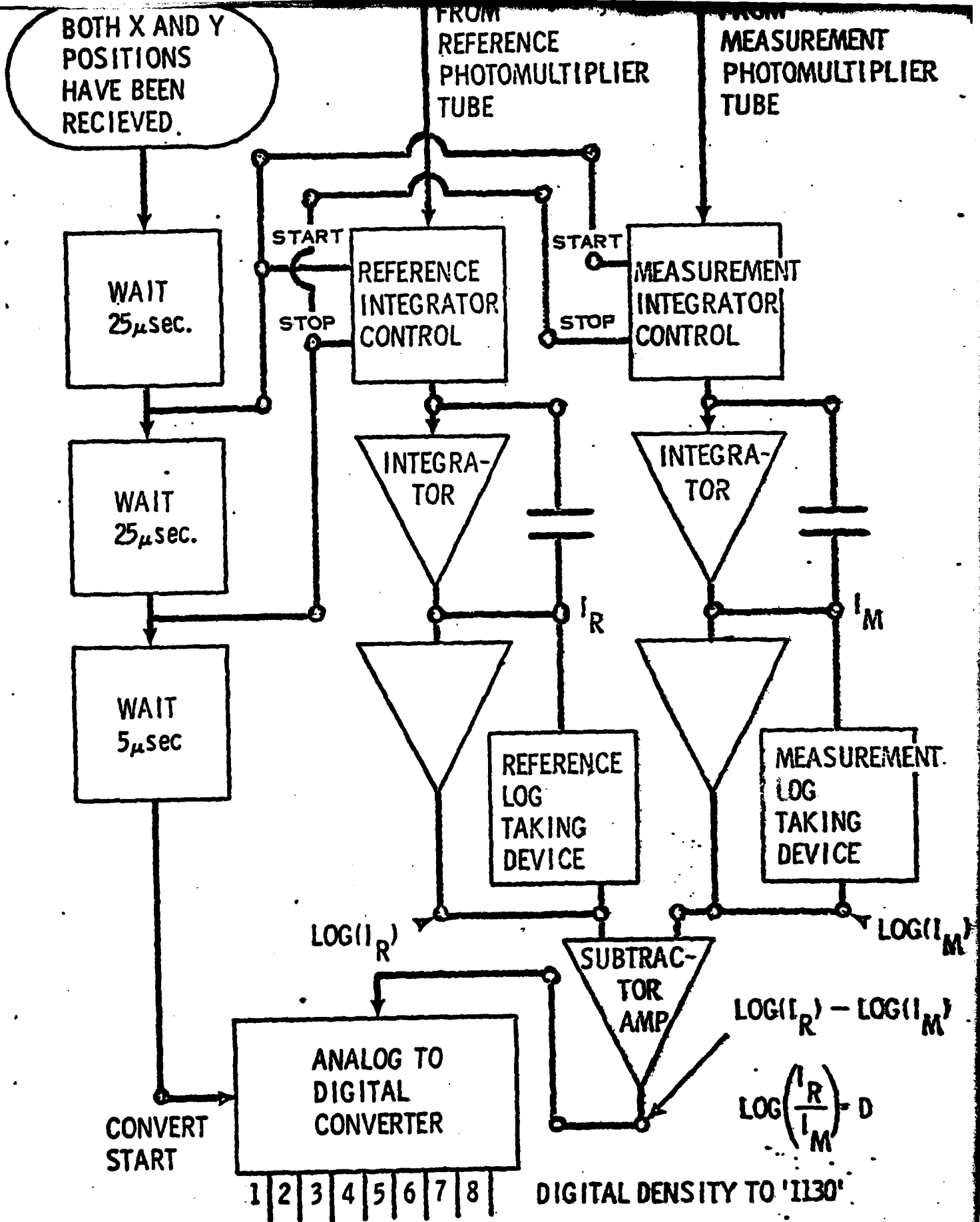


Figure 2



Figure 10

The DXCP system hardware. From left to right: the tall cabinet on the left houses the scanning CRT and the photomultiplier tubes; the other tall cabinet contains the power supplies and control circuits; the boxes on top of these cabinets contain the computer interface components; next is the Tektronic 611 storage scope and the 2311 hard copy unit; the IBM 1130 computer is on the right.



Figure 11

Contents of the cabinets shown on the left in Figure 10: In this photograph, the scanning CRT and photomultiplier circuits are in the cabinet on the right; the other cabinet contains the power supplies and other associated circuits.

B. Data Acquisition

An analysis of the information content of the panoramic radiograph produced by a Panorex Dental X-ray machine revealed the following conditions that had to be taken into consideration and utilized in the development of the data acquisition algorithms:

1. the images of the teeth occupy only about 25% of the panoramic radiograph;
2. there is considerable variation in the general appearance of the image of the dental arches in the panoramic radiograph, both with respect to their position on the film and the relative position of adjacent bony structures of the skull;
3. the resulting image of the incisal and occlusal surfaces are sensitive to head position during the exposure, so that the dental arches could appear either convex, flat or concave depending on the inclination of the occlusal plane during the exposure;
4. there is considerable variation in the overall density of radiographs of different people due to individual variation in head size, and bone density and structure; and
5. images of similar structures (i.e. dentin) in the same radiograph have different absolute densities, so that there is no way of establishing an absolute density mapping that would be applicable to all areas in a given radiograph;

6. the inter-arch space was always darker (i.e. was of greater optical density) than the bordering teeth or edentulous areas;
7. the boundaries between the occlusal/incisal surfaces of the teeth and the anterior border of the ramus of the mandible, and the inter-arch space were almost always characterized as "high contrast" boundaries relative to other boundaries in a given radiograph;
8. the image of the mesio-incisal angle of the upper and lower central incisor teeth always appeared in a finite bounded region of the radiograph, about 1" square;
9. the shape of the tooth images are such that the root boundaries are approximately at right angles to the occlusal/incisal edges;
10. the images of the root portions of the teeth were approximately rectangular in shape, with the long-axis of the rectangle perpendicular to the occlusal/incisal surface.

Based on these observations, the following procedure was developed to:

a) automatically direct the system to a readily identifiable starting point in the radiograph; b) direct the scanner to gather sufficient information to define the occlusal and incisal boundaries of the upper and lower teeth, or the ridge boundary in the case of missing teeth; and c) direct the scanner to gather sufficient information to define and identify the root boundaries of existing teeth.

The procedure consisted of two parts: a) a technique for recording a fiducial mark in the radiograph in a specified position relative to the teeth; and b) a heuristic computer program to direct the scanner to sample the density of the radiograph in a specified manner.

Fiducial Mark Recording:

1. At the time the radiograph is taken, a plastic bite-block (about 5/16" thick) with a small piece of wire embedded in it was inserted in the subject's mouth and oriented so that the long-axis of the wire-insert was parallel to the long-axis of the teeth and located at the mid-line of the dental arches; this technique provided a means of readily identifying the mid-line of the dental arches on the radiograph, and insured the separation of the upper and lower teeth and the existence of an "inter-arch" space in the resulting radiograph. See Figure 12.

Heuristic Processing Algorithm:

1. The first step in the processing algorithm consists of a sequence of horizontal scans in the bounded region in which the radiographic image of the bite-block wire is expected; this scan continues until the image of the wire is detected and verified based on size and shape parameters. See Figure 13.
2. Using the mid-point of the wire as a starting point, a horizontal scan is initiated extending distally from the wire until the boundary between the inter-arch space or lower (upper tooth is detected; from this intersection point a vertical scan is



(a)



(b)

Figure 12

Raster scan (a) and iso-density curve display
(b) of panoramic dental radiograph with fiducial
wire mark at mid-line of dental arches.

initiated until the boundary between the inter-arch space and an upper (lower) tooth is encountered.

3. Using the mid-point of the line joining this pair of upper and lower boundary points as a starting point, step (2) is repeated; this "stair-case" procedure is repeated until the anterior border of the ramus of the mandible is detected. See Figure 13.
4. A second-order least square curve is fitted to the set of upper, and the set of the lower arch boundary points, approximately the occlusal-incisal surfaces of the teeth; these curves are used to define the trajectories for the root-scans of the respective arches. See Figure 14.

Note: If the head position was such that the image of the arches were flat, rather than concave, the anterior border of ramus would be intercepted on the first search scan from the mid-line wire in this case, the occlusal-incisal surface could be approximated by the straight line.

5. Starting at the center of the mid-point of the wire, a line is defined parallel to the long axis of the wire-this line marks the mesial extent for the root scans; again, starting at the center of the wire, a distance d is marked off along this line in an upper and lower direction - using these points as starting positions, and following a trajectory as defined in step (4), data is collected at a specified sampling frequency and stored in the computer; the starting

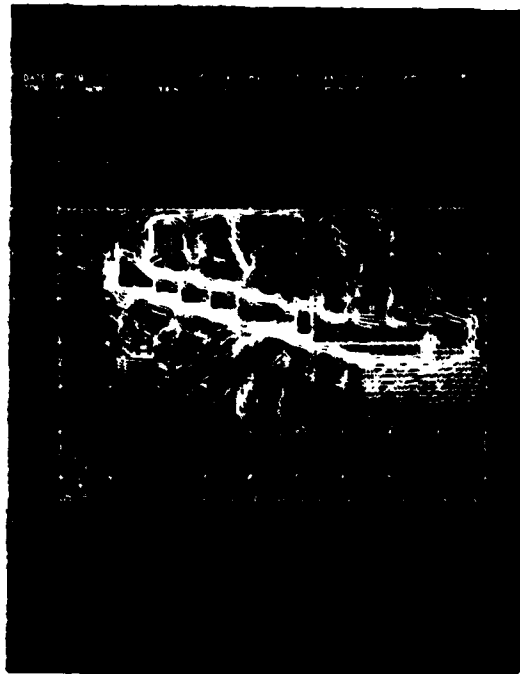


Figure 13

Computer-guided search for the fiducial mark, and the "stair-case" scan to define a set of points on the boundary between the inter-arch space and the upper and lower teeth.

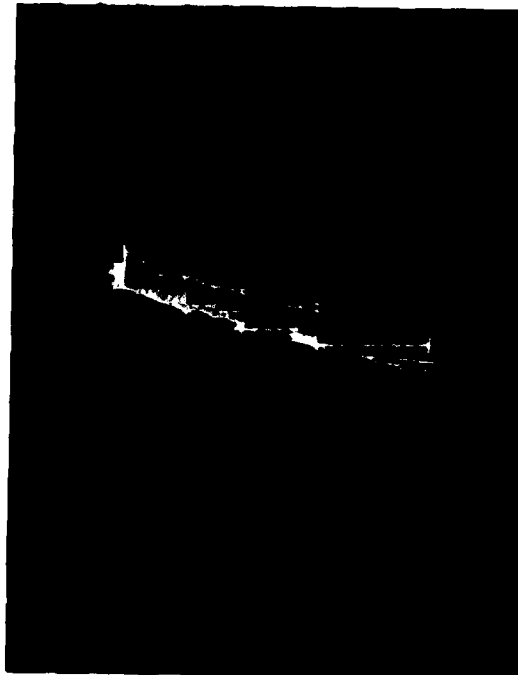


Figure 14

Least-square curves determined by the set of points defined by the "stair-case" scan procedure super-imposed on the scan trajectories of the fiducial mark search and the stair-case scan.

point is then moved apically from the previous position by a specified amount and this root-seam process is repeated until ten such root scans have been completed. See Figure 15.

6. Starting at the mid-line wire, and extending distally, a series of up and down scans are performed to define the boundaries between the interarch space and the occlusion-incisal edges of the upper and lower arches. See Figure 16.

At this point, eleven data vectors are stored in the computer for each arch: ten root scan vectors and one occlusal-incisal edge vector. The set of vectors for each arch contains approximately 4000 data points and contains sufficient information to define the outlines of the teeth in each arch, if they are present. This technique represents a marked reduction in stored data points as compared to storing the digitized image of the entire radiograph (i.e. about 4000 vs 1,000,000 data points). See Figure 17.

C. Information Processing

As stated in Section II, Mathematical Concept of Picture Processing, a picture can be described in terms of the density at every point in the picture in the spatial domain, or in terms of frequency and amplitude in the frequency domain. Sharp boundaries were also defined as consisting of essentially high-frequency components and the inclusion of low-frequency components tendency to make the boundary fuzzy and less distinct. A picture with "soft" boundaries could be enhanced by filtering out the low-frequency components by a suitable high-frequency filter, and when transformed back into the spatial domain the picture would appear "sharper".



Figure 15

The ten root scan trajectories.



Figure 16

The scan to determine the actual boundaries between the inter-arch space and the occlusal/incisal edges of the upper and lower teeth, and the scan trajectories of the root scans.

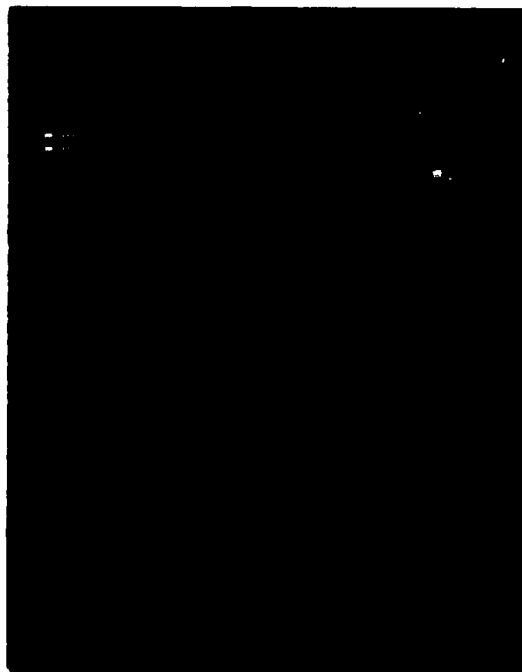


Figure 17

The data vectors produced by the root scan procedure.
These vectors contain the densities of the sample
points along the root scan trajectories.

Just as a picture has both a spatial and frequency domain representation, so does a "filter". While picture enhancement can be accomplished by filtering in the frequency domain, the transformation from the spatial domain to the frequency domain application of the frequency domain filter and then transformation back to the spatial domain is very time consuming process, even on very fast computers.

An alternative approach is to develop a suitable filter in the frequency domain and find its equivalent representation in the spatial domain. It can be shown that the process of filtering, or convolution in the frequency domain (or the power spectrum equivalent which is the "square" of the frequencies) can more easily be accomplished by viewing the density data in the spatial domain through an aperture window of varying transmission. Such a "window" consists of a set of weights which is the spatial domain equivalent of the frequency domain filter. Each data point (i.e. density at point x,y) is replaced by the result of the weighted average of the given point and its neighbors. See Figure 18.

Different sets of weights will produce different "filtering" or smoothing effects. Actually, what is used is a "band pass" filter that will remove the low frequency components that cause fuzziness of the boundaries, and also remove the very high frequency "noise" that has the effect of introducing "false boundaries" or artifacts into a picture.

These filters, or sets of weights must be determined very carefully, as to "heavy" a filter will smooth out the data to such an extent so as to eliminate all boundary indicating and to "light" a filter will have virtually no effect, or may even accentuate the "system noise" by creating an effect called "ringing".

Fixed memory (non-recursive) and fading memory (recursive) band-pass filters were used to enhance the root scans. Examples of the transfer function of these filters are illustrated in Figure 19(a,b,c); the upper curve and middle curve correspond to a non-recursive and recursive filter, respectively, and the lower curve is a plot of the difference between the two filters.

While the behavior of both types of filters were about the same in the desired band-pass region, the recursive (fading memory) filter performed better outside of the band-pass region as evidenced by the lack of ringing at higher and lower frequencies.

These band-pass filters were used to:

- a) remove the low-frequency components generated by the blurred-out images of structures outside of the focal trough of the Panorex dental x-ray imaging system; and
- b) to reject the high frequency components corresponding to film grain, quantum noise produced by the intensifying screens, and small variations in density within the tooth image itself due to anatomic and structural variations of the tooth itself (i.e. pulp chamber) and of the supporting bone (i.e. bone trabeculae).

Application of these frequency domain filters require about 5 minutes of computer time due to the need to transform the raw data from the spatial domain to the frequency domain and back to the spatial domain after the filter was applied. By calculating the spatial domain representation of these filters and using the resulting weighting function directly on the raw scan data, processing time was reduced to about 10 seconds per scan!

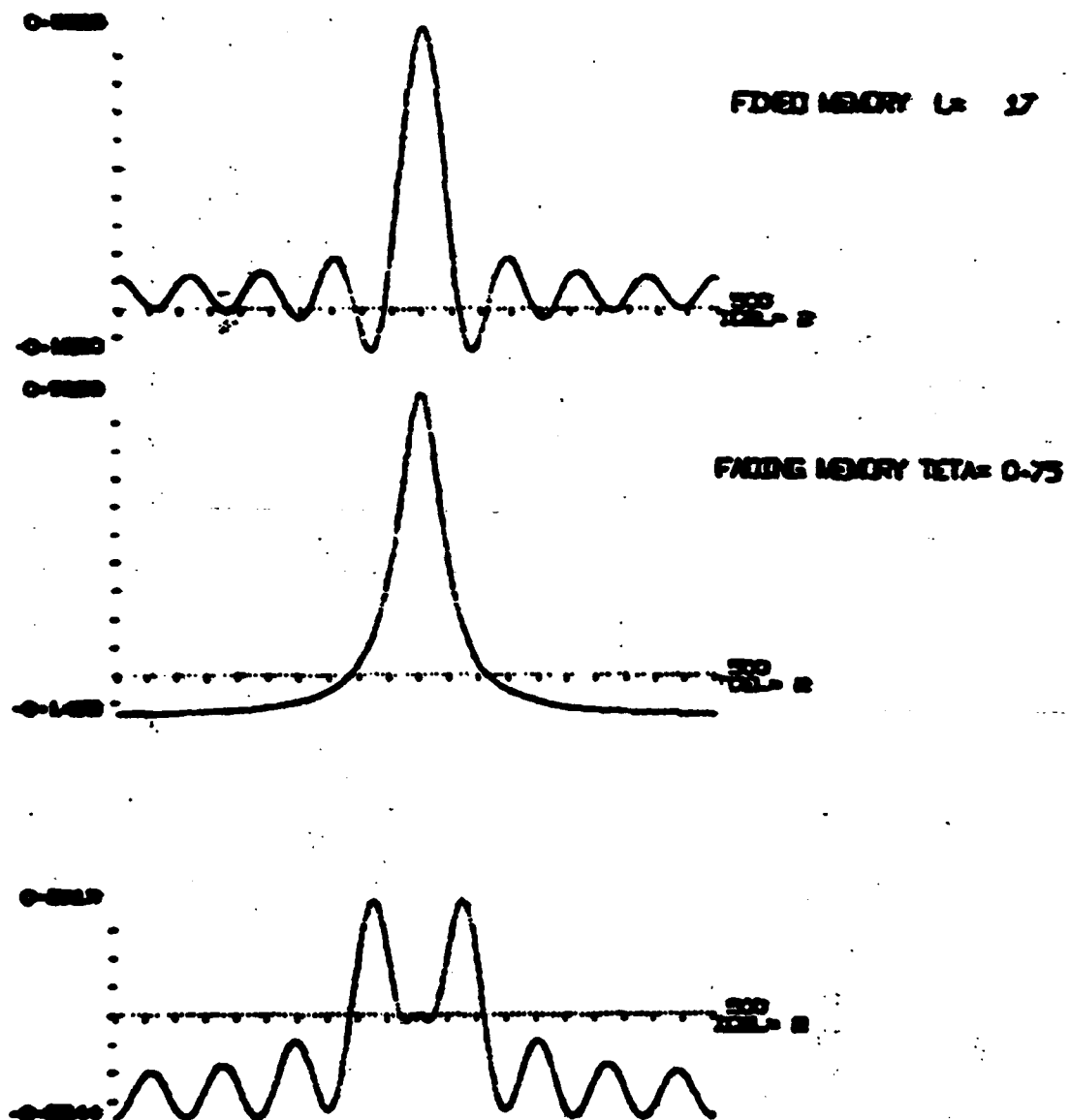


Figure 19(a)

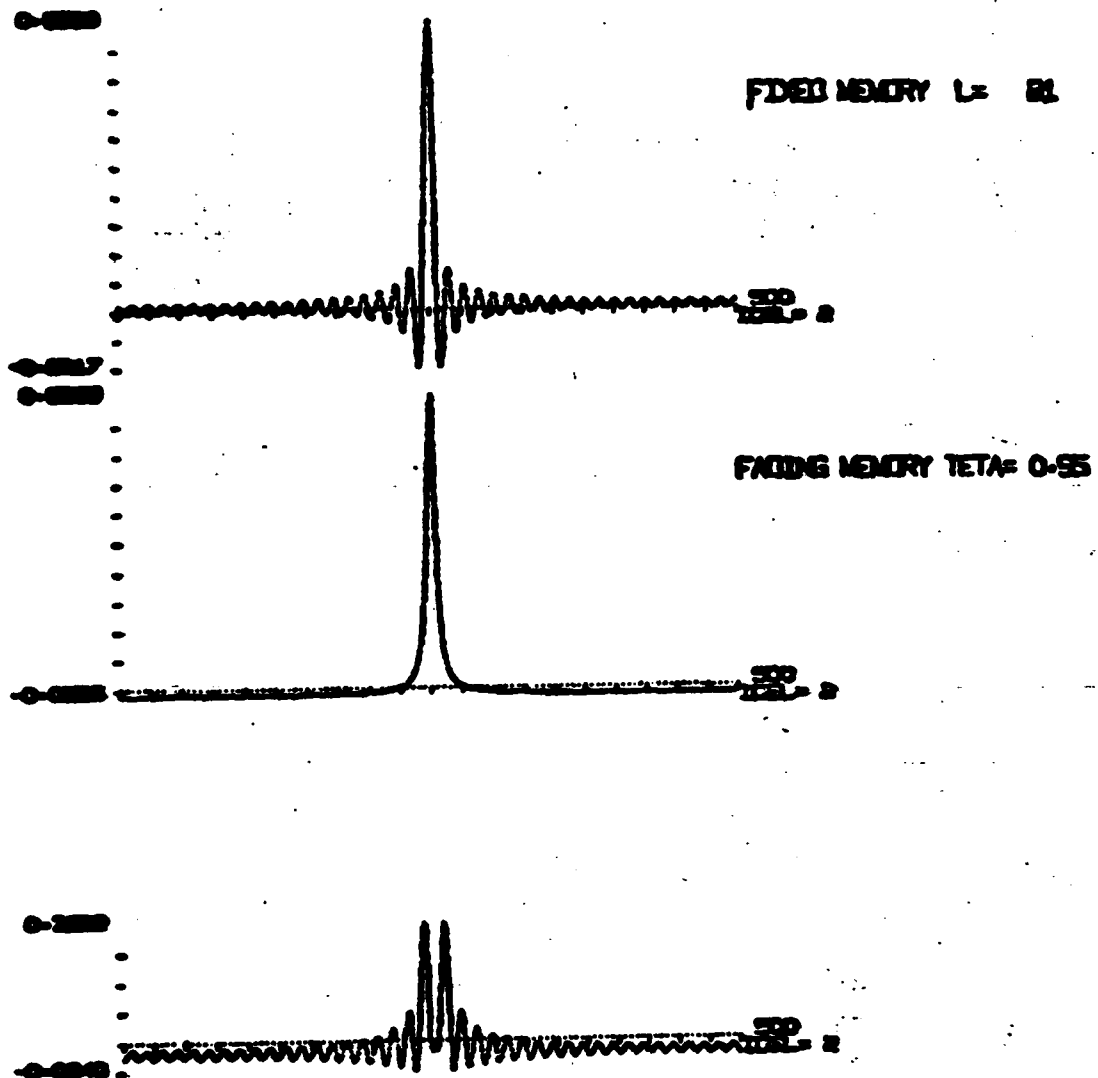


Figure 19(b)

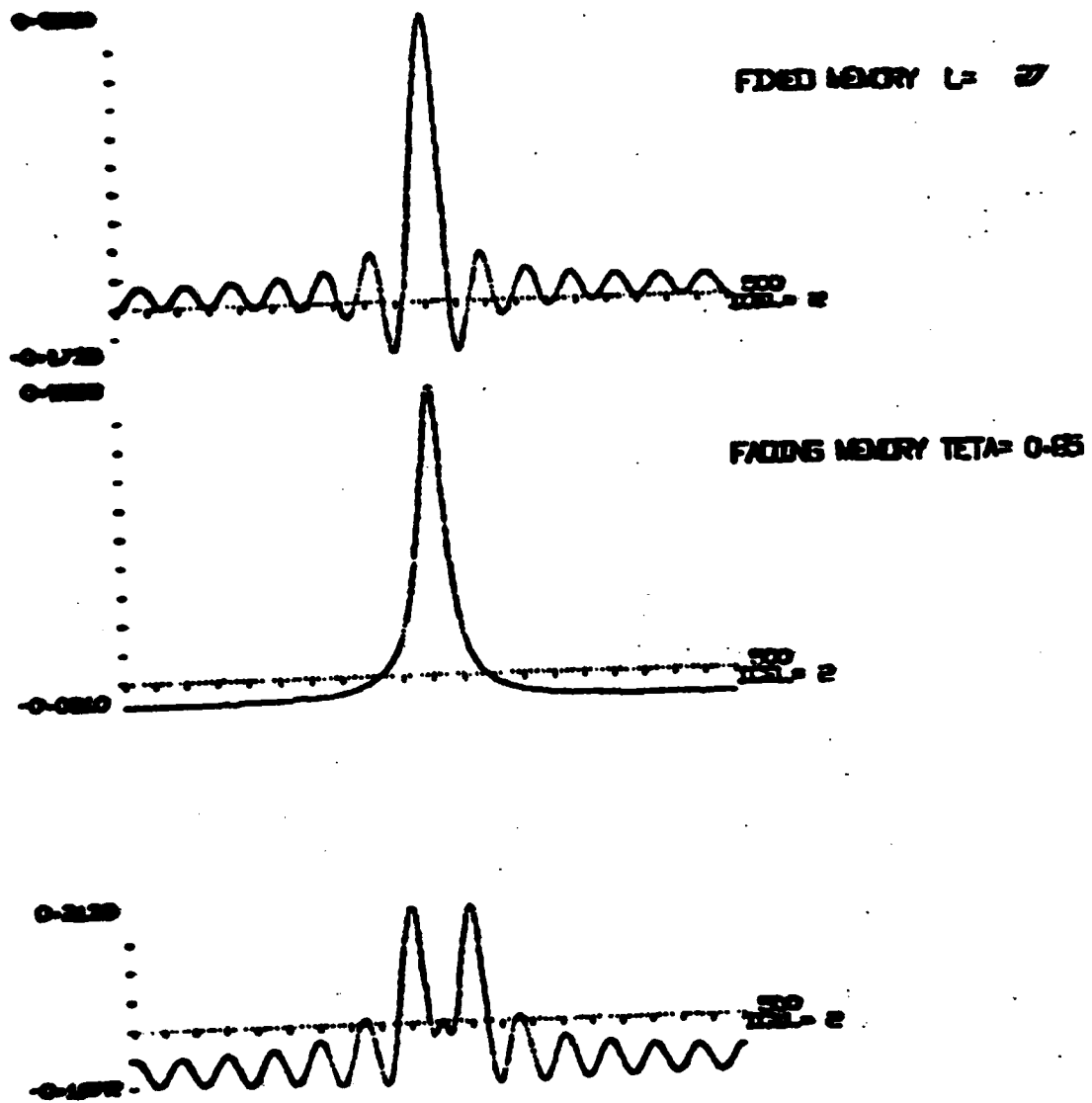


Figure 19(c)

Figure 20(a) shows the ten enhanced root scans platted in a serial manner - note how the hills and valleys correspond to the root contours of the original radiograph (refer to Figure 12). Figure 20(b) is a display of the computer analysis of the occlusal/incisal surface scan of the same radiograph. The reconstruction of the teeth images from the root scans and occlusal/incisal surface scan is shown in Figure 20(c). Thus this information (for one quadrant only) can be used to fill in a dental chart is illustrated in Figure 20(d).

Figure 21 is an isodensity scan of a panoramic radiograph with missing teeth. Figures 22(a)-(d) show how the computer can detect the missing teeth and report out the results accordingly.



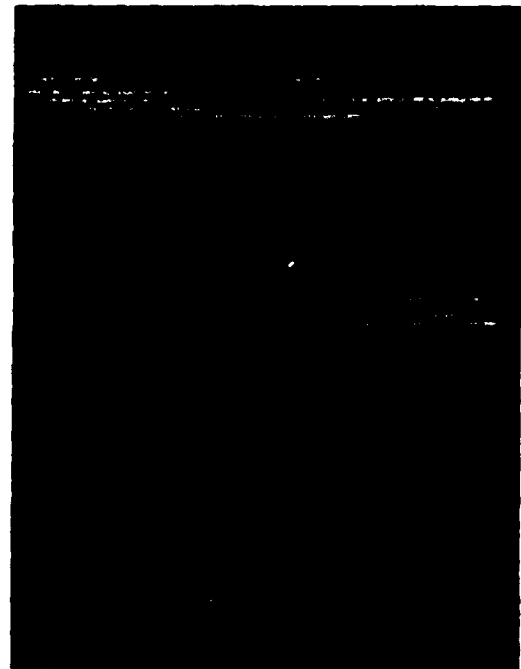
(a)



(b)



(c)



(d)

Figure 20

See text for details.

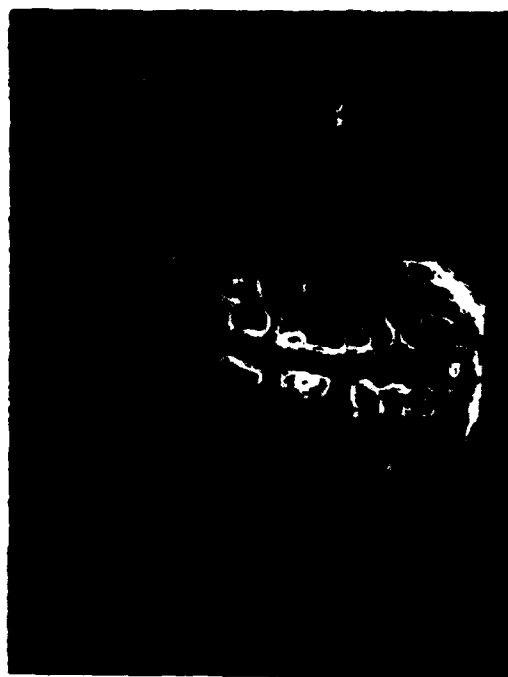
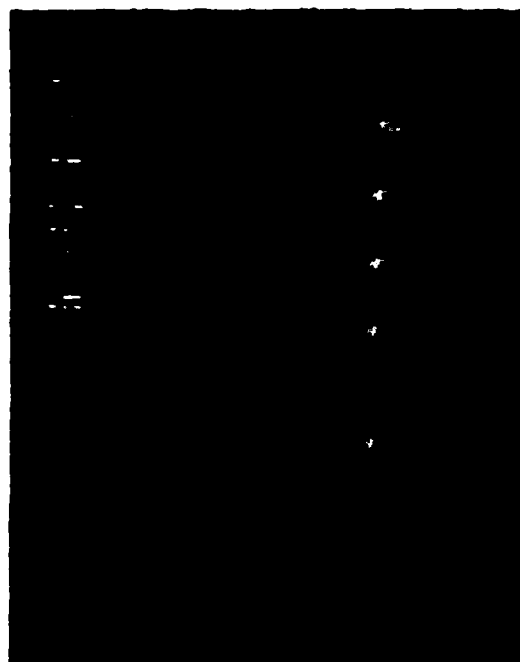


Figure 21

Isodensity plot of panoramic radiograph
with missing teeth in lower jaw.



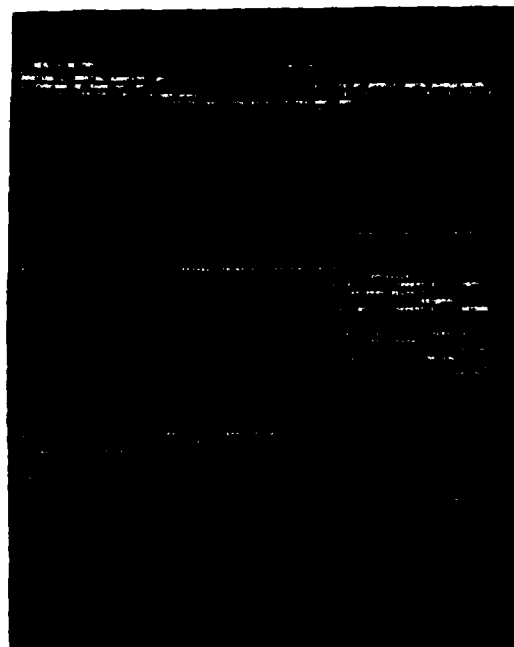
(a)



(b)



(c)



(d)

Figure 22

See text for details.

Just as various patterns of density change on a global level were used to identify the presence of teeth, an analysis of the density patterns within these tooth outlines could be used to identify the existence of certain conditions within the teeth.

For example, Figure 23 is an isodensity scan of a lower molar tooth. There is a small area of decay on the right side - note the very distinctive change in the isodensity curves in this area as compared to the left side which is non-carious.

The pattern of a large area of decay is illustrated in Figure 24. In this bi-cuspid tooth, the entire right side is destroyed by caries - again, note the significantly different pattern of this area as compared to the non-carious left side.

A metallic restoration, which radiographically appears as a clear area with a very distinct boundary, can be readily identified in the tooth illustrated in Figure 24. The sharp boundary is characterized by a steep density gradient, and consequently the isodensity contours in the region of the boundary are tightly bunched together. The clear area corresponding to the metallic restoration has a very uniform appearance on the radiograph and this region has very few, if any, different density levels. The well-delineated area on the left side of this tooth below the radio-opaque area of the filling is recurrent decay.

From these three illustrations, it is evident that normal tooth structure, caries and metallic restorations have characteristic density patterns that are not only visible to the eye on a radiograph, but also have very characteristic and distinctive density patterns that are capable of being recognized by computer programs.

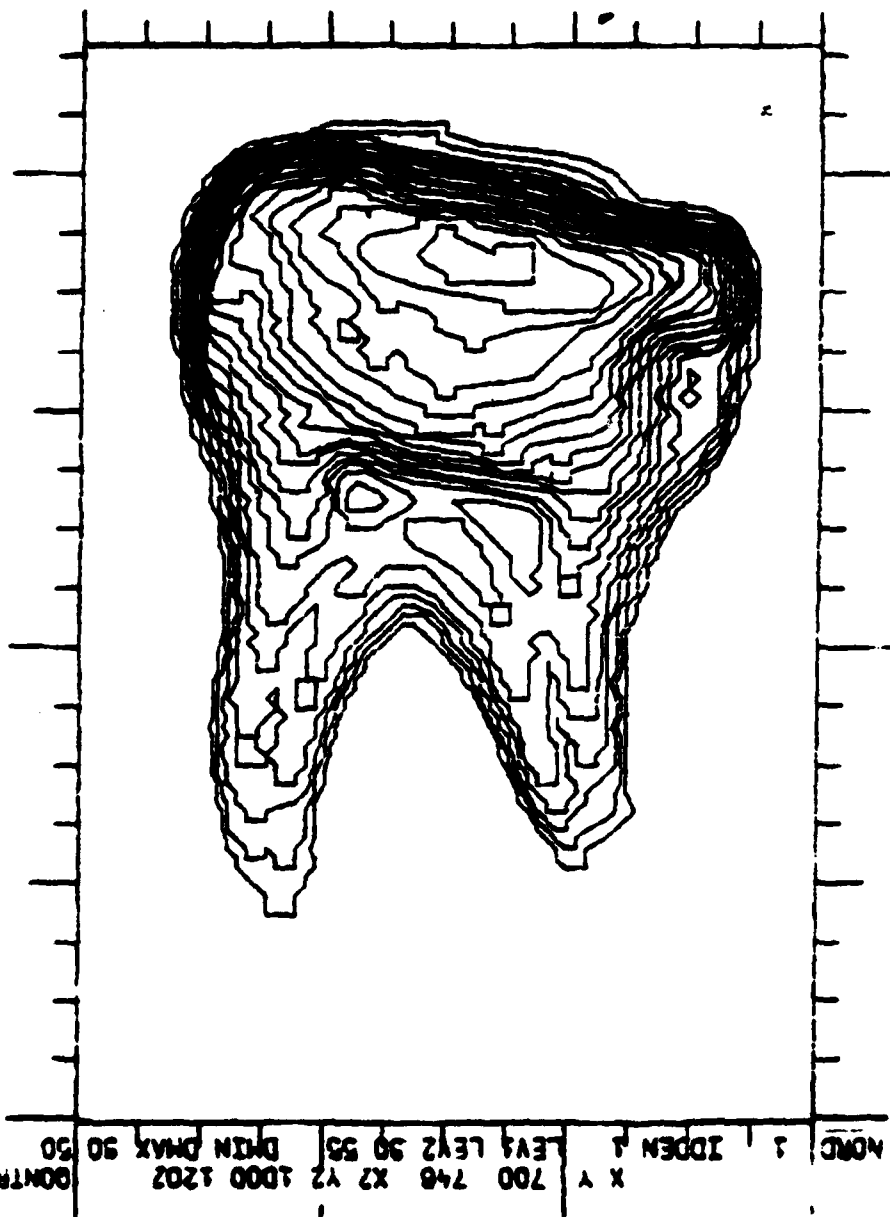


Figure 23

IDEL	9	NORD	0	IDDEN	1	X Y	275	421	X2 Y2	575	677	CONTR	PAGE	30
				LEV	1	LEV2	30	0	DMIN	DMAX	30	44	NASFY	100

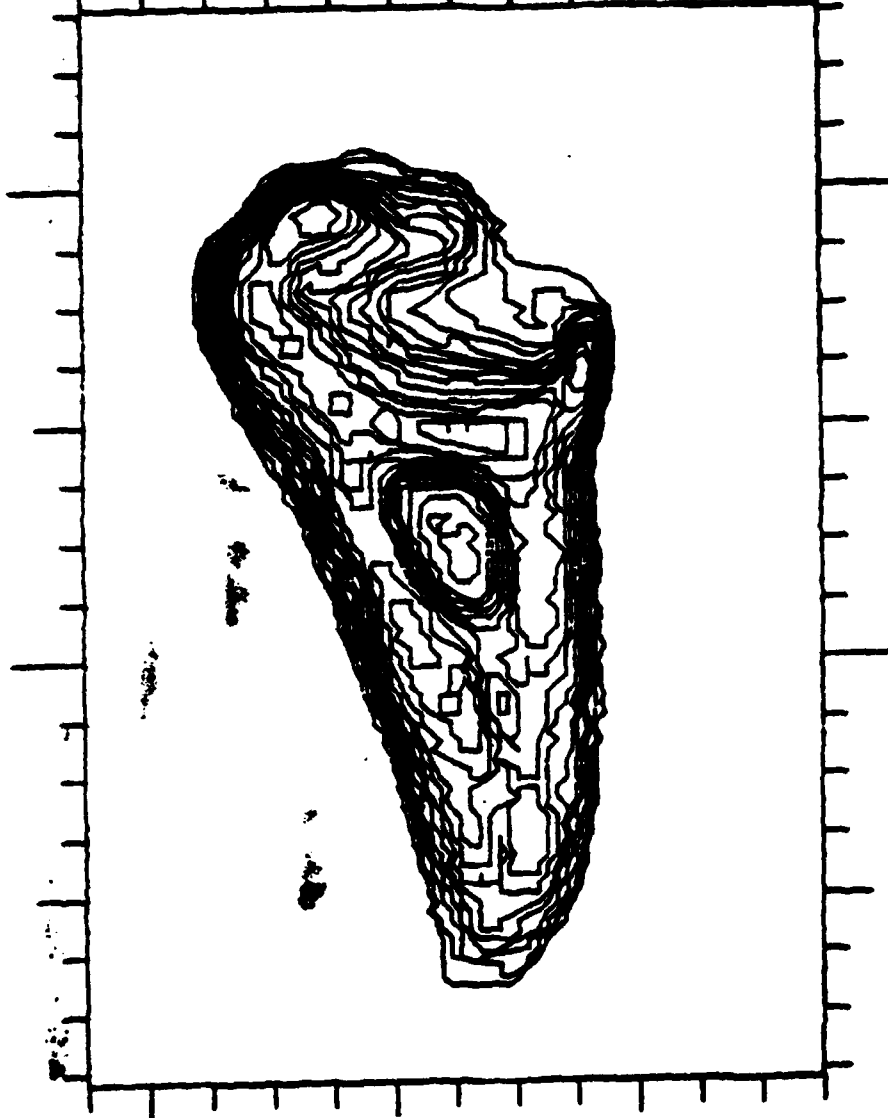


Figure 24

DEL	NORD	1	IDEN	1	X Y	550 671	XZ YZ	900 1127	CONTR	PAGE	35
					LEV1	LEV2	28 50	DNIN DNAX	28 50	MAGFY	400

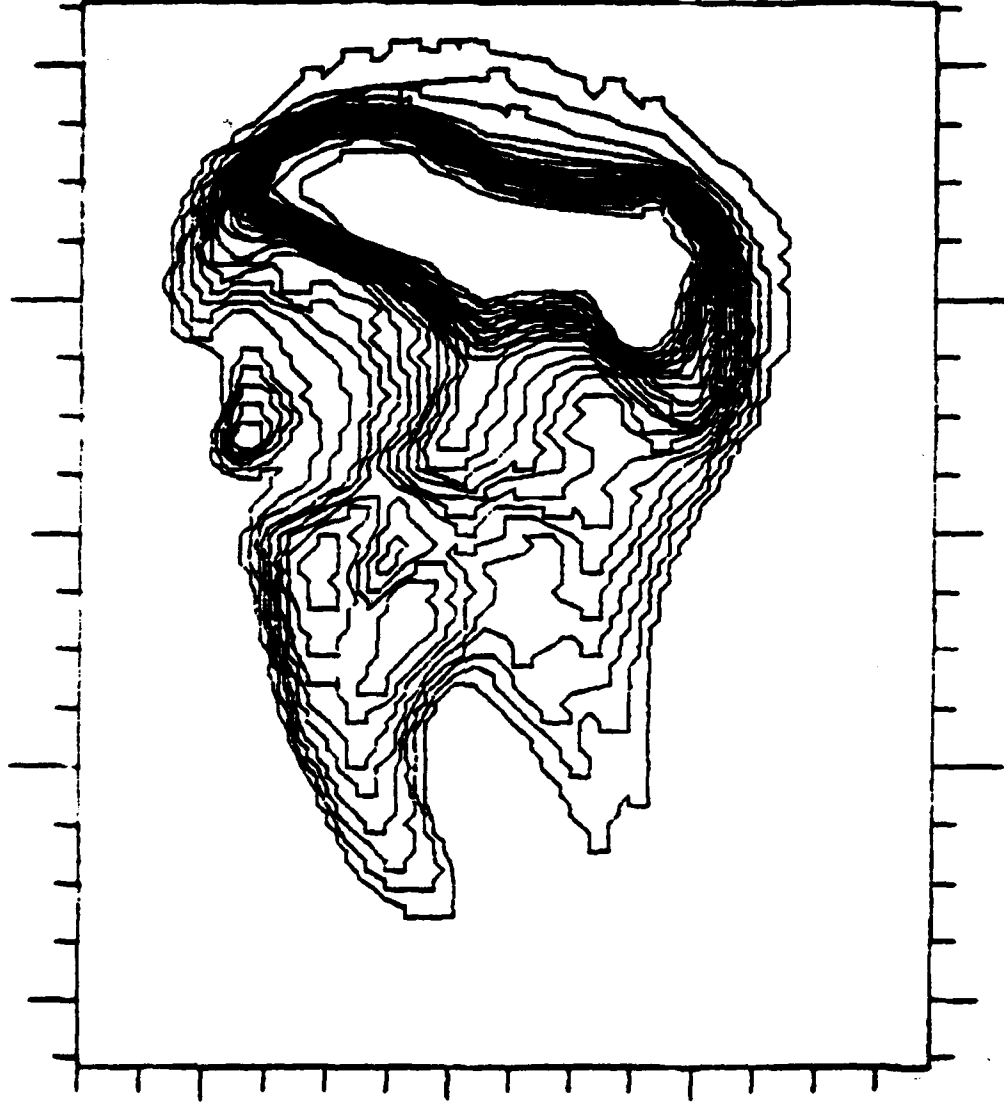
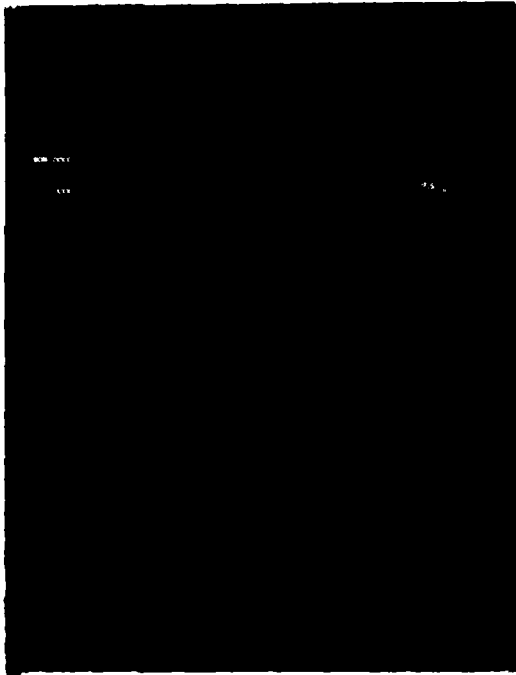
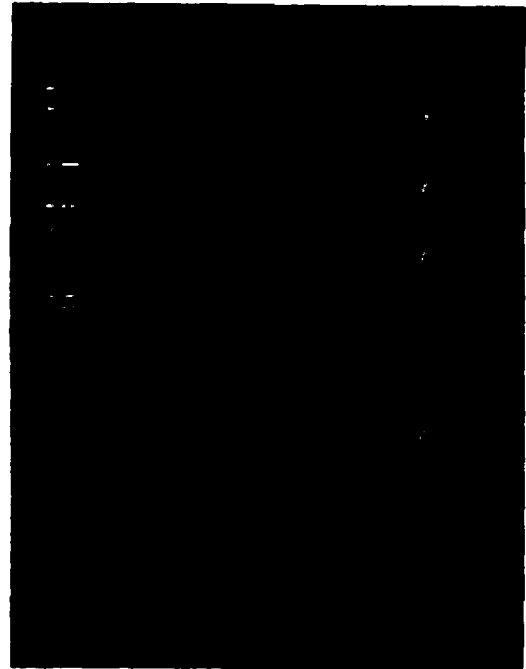


Figure 25

Accordingly, the next step after identifying the boundaries of the teeth, is to examine the interior of the regions defined as "teeth" to identify such conditions as the existence of metallic (or other radio-opaque) restorations and caries. Computer programs were developed to do a "star-scan" in an area within the tooth boundary corresponding to the crown of the tooth. Figure 26(a) illustrates how the computer program is able to identify the crown of the lower first molar. The center of this area was determined and a series of radial scans executed beginning at the center and terminating at the outer boundary of crown region. See Figure 26(b). These density vectors contain sufficient information, both with respect to density changes and position of these changes within the tooth, to identify radio-opaque restorations and decay. However, the program to analyze this data have not been implemented.



(a)



(b)

Figure 26

The interior radial or "star" scans.

V. Results and Conclusions

The ability to scan a panoramic dental radiograph and extract sufficient information to identify the presence or absence of teeth has been demonstrated, and procedures to do a detail scan on the areas of the radiograph corresponding to those teeth present have been developed. The characteristic density patterns associated with normal tooth structure, radio-opaque restorations and decay have also been identified. These procedures and techniques were demonstrated on a set of original panoramic radiographs taken of actual people.

There were, however, difficulties encountered in the successful application of the scanning and evaluation process to all radiographs: either the process would not work, or only a part (i.e. a quadrant) of a radiograph could be correctly evaluated. These difficulties were attributable to essentially two conditions:

1. The diagnostic quality (i.e. contrast and detail) of all radiographs was not consistent - in some instances the image was so poor that it was not possible for a human evaluator to "objectively" read the radiograph; and
2. Variations in head position and individual bone structure resulted in radiographs with varying degrees of "noise" due to the superposition of only partially blurred-out anatomic structures on the tooth images.

In many cases, more attention to the manner in which the radiographs were taken and better control over the developing procedure would have produced radiographs that would probably have been scanned with greater reliability.

For some others, however, additional effort is required to:

1. Develop a mechanism to dynamically adjust the density range to compensate for the extreme light or dark regions encountered, and to establish a normalized density range for each radiograph; and
2. To develop filters with greater sensitivity and discrimination ability to reject noise patterns caused by anatomic variation - this is especially true for the upper jaws where the images of the maxillary sinus, orbits, zygomatic arch, nasal fossae and hard palate frequently are superimposed over the images of the upper teeth.

From a technological point-of-view, there has been little improvement in the basic scanning apparatus (i.e. scanning CRT and photomultiplier tubes). However, there have been dramatic advances in logic circuit-design and fabrication, so that much of the older circuitry could now be replaced with micro-processors on chips, and a mini-computer could be used in place of the 1130. This could result in a smaller unit with increased processing speed and the ability to perform much more complex picture processing procedures at a lower overhead.

It is generally believed that if these basic features recognition algorithms (with the modifications incorporated as described above) could be implemented on a system reflecting the newer computer technology, it would be possible to upgrade the system so that there would be a marked improvement in the performance of the DKCP scanning system with respect to both processing speed and system reliability.

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